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Vertisols and Cambisols had contrasting short term greenhouse gas responses to crop residue management

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Abstract: In sustainable agriculture crop residues management should consider the interactions between soil and residue properties, which can affect the decomposition and global greenhouse gases (GHGs) emission. Through a laboratory experiment, we investigated the effect of the management (incorporation and surface placement) of wheat and faba bean residues on their decomposition and CO_2, CH_4 and N_2O emissions from two soils, a Chromic Vertisol and an Eutric Cambisol. In the Vertisol, wheat residues increased the CO_2 emission more than faba bean when left on the surface whereas no differences among residues were observed when incorporated. In the Cambisol, faba bean emitted more than wheat when left in the surface and less when incorporated. Total CH_4 emissions were higher in faba bean in Cambisol for both management and only when applied in the surface in Vertisol. Total N_2O emission in the Vertisol was higher when faba bean was incorporated, and wheat was left on the surface. In the Cambisol, wheat addition increased total N_2O emissions by 20% compared to faba bean, with no differences between managements. Our study confirmed that contrasting properties among tested soils resulted in significant interactions with residues own degradability and their placement affecting residue decomposition, soil C and N dynamics, and GHGs emission.

Keywords: sustainable management; carbon dioxide; nitrous oxide; methane; soil texture

Agriculture and land use are responsible for about 25% of the global greenhouse gas (GHG) emissions (IPCC 2014). Crop residue management is critical to agroecosystems, transferring nutrients within and between rotations and it is of significant importance in improving nutrient turnover and soil fertility, affecting especially microbial activity and thus carbon (C) and nitrogen (N) dynamics, and GHGs emissions (Rees et al. 2013). A number of soil properties are important in controlling residue decomposition, including porosity, pH, texture, moisture content, temperature and oxygen diffusivity, all of which regulate soil connectivity and thus also GHGs emissions (Badagliacca et al. 2017, Song et al. 2019). Together with soil properties, placement of residues can have strong effects on their decomposition and GHGs emissions to the atmosphere (Tang et al. 2015, Jahanzad et al. 2016). Several experiments have highlighted that the location of crop residues can influence physical, chemical and biological properties of soil microsites (Giacomini et al. 2007) and also that crop residue characteristic, other than the C:N ratio, are implied in such changes (Jahanzad et al. 2016), leading to variable and often contradictory results (Nicolardot et al. 2007, Maisto et al. 2010, Han et al. 2017). The same uncertainties in decomposition are associated

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with GHGs production and in particular for N_2O emissions (Baggs et al. 2003, Nett et al. 2016). In a previous study, Badagliacca et al. (2017) had shown that, when crop residues were buried, straw and soil properties may interact each other leading to different levels of CO_2 and N_2O emission. Therefore, starting from those observations, in this study we focused on the role of residue placement on short-term emissions of CO_2, CH_4 and N_2O in a Chromic Vertisol with a high clay, pH, and inorganic C content and an Eutric Cambisol with a sandy-loam texture, low clay and pH. We hypothesised that variation in the soil availability of substrates for microbes (dissolved organic C, ammonium and nitrate) and the subsequent emissions of GHGs (CO_2, CH_4 and N_2O) would be affected by the interaction between soil type, residue types with similar C:N ratio, and their placement (incorporated or left on the surface). In particular, we hypothesised that degradation and emission could be stimulated by incorporation in the Cambisol, due to the higher soil organic matter concentration capable to supporting a wider soil microbial community and the sandy-loam texture which allows for greater aeration and displacement of the gases, whereas in the Vertisol, higher GHGs emission fluxes should be associated with the surface application, rather than incorporation, due to the higher organic matter physico-chemical protection from clay that could promote its stabilisation and the finer soil particles that could limit soil micropore and aeration. It was also assumed that wheat residues should lead to higher GHGs emission than faba bean residues due to its higher degradability (low lignin), allowing greater interaction with placement.

MATERIAL AND METHODS

Experiment setup. A pot experiment was established under controlled conditions in a completely randomised factorial design with three replicates. Treatments tested were: soil type (Eutric Cambisol and Chromic Vertisol; WRB 2014); plant residue species (durum wheat, *Triticum durum* Desf. (Wh), and faba bean, *Vicia faba* L. (Fb)); residue placement (incorporated in the soil volume (Inc) or distributed evenly over the soil surface (Sur)). Soils were collected from the top 20 cm of an experimental site at the Bush Estate (55°51'N, 3°12'W; 199 m a.s.l.) near Edinburgh (Scotland, UK) and from the Pietranera Farm (37°30'N, 13°31'E; 178 m a.s.l.) in Santo Stefano Quisquina (Sicily, Italy), respectively for Cambisol and Vertisol. At both sites, the soil was collected in conventional tilled experimental plots previously cultivated with cereals. The main properties of soils used in the study are presented in Table 1. Before establishing the experiment, each soil was air-dried, sieved, and visible roots and raw organic residues removed, and then the soil was thoroughly mixed. The water holding capacity of both soils was determined on a mass basis. Pots used for the experiment had a diameter of 10 cm and a height of 15 cm and were filled with 1.5 kg of soil to achieve a bulk density of 1.25 g/cm^3. Oven-dried crop biomass of durum wheat (*Triticum durum* Desf. cv. Simeto) and faba bean (*Vicia faba* L. cv. Gemini) cultivated at Pietranera farm, was ground, mixed, and used as crop residues according to the treatments: mixed in the soil volume or distributed evenly over the soil surface at a rate of 5 g crop residue per kg of soil. For both soils, control pots have been prepared without the addition of residues. Soils were brought to 60–70% of the water holding capacity at the beginning of the experiment and the moisture content was maintained constant during the whole experiment adding to each pot an amount of water corresponding to the evaporation losses after each measurement interval. The main properties of the residues used are presented in Table 2. Soils were incubated for 7 weeks in a naturally lit greenhouse where the temperature was maintained between 20 °C and 22 °C.

Table 1. The site and soil properties

Soil property	Eutric Cambisol	Chromic Vertisol
Soil series	Macmerry	Sulphurous-chalky
Texture	sandy-loam	clay
Coordinates	55°51'N, 3°12'W	37°30'N, 13°31'E
Altitude (m a.s.l.)	199	178
Slope (%)	6	7
Clay (%)	12.7	52.5
Silt (%)	15.7	21.6
Sand (%)	71.6	25.9
pH	6.6	8.1
DOC (mg/kg)	58.2	22.5
Field capacity (pF 2.5) (%)	36	38
Permanent wilting point (pF 4.5) (%)	20	16
Organic matter (%)	4.3	2.4
Total organic carbon (%)	2.5	1.4
Total nitrogen (%)	0.21	0.13

DOC – dissolved organic carbon

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Table 2. Chemical and fibre composition of the crop residues (%)

Chemical property	Durum wheat	Faba bean
Organic matter	92.1	91.8
Carbon	39.6	41.0
Nitrogen	1.3	1.4
Crude protein	8.1	8.8
Ether extract	1.7	1.1
Acid detergent fibre	28.8	48.0
Acid detergent lignin (ADL)	3.5	10.0
Cellulose	25.3	38
Neutral detergent fibre	45.4	54.0
Hemicellulose	16.6	6
Ash	7.9	8.2
ADL ash	3.2	0.4

Soil GHGs fluxes and soil chemical measurements. Measurements of CO_2, CH_4 and N_2O emissions were made three times per week on 22 sampling occasions with Photoacoustic Gas Analyser (PGA, INNOVA 1412, LumaSense Technologies A/S, Santa Clara, USA). At each sampling time, emissions from pots were randomly measured between the 9.00 and 12.00 a.m. The PGA was connected by two small rubber pipes to a PVC chamber with a diameter of 10 cm (surface 78.5 cm^2) and a height of 10 cm and sealed above the pot by a rubber gasket to ensure a gas-tight seal between pot and chamber. The PGA instrument was calibrated in the lab for CO_2, CH_4 and N_2O by the LumaSense and its detection limits were of 1.5 ppm for CO_2, 0.55 ppm for CH_4 and 0.03 ppm for N_2O. The instrument sampled the air from inside the chamber and performed the analysis with a 5-second sampling integration time and a fixed flushing time between measurements (8 s). The equipment performed built-in compensation for water and cross interferences among target gases. Each sampling and GHGs (CO_2, CH_4 and N_2O) concentration measurement taken approximately 70 s and each measurement was made every 2 min. Four measurements per pot were carried out. Soil CO_2, CH_4 and N_2O fluxes were calculated by linear regression of gas concentration increase inside the chamber over the closing time corrected for the chamber air temperature according to Jantalia et al. (2008) and Vitale et al. (2018):

$$f = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \frac{m}{V_m} \quad (1)$$

where: $\Delta C/\Delta t$ – gas increment during the chamber closure; V – volume of the chamber; A – soil area; m – molecular weight of the gases and V_m – gas molar volume corrected for the ambient temperature. The total amount of CO_2, CH_4 and N_2O emissions were calculated by linear interpolation between consecutive sampling events using the following equation (Cheng et al. 2012):

$$\text{Cumulative } CO_2 \text{ or } CH_4 \text{ or } N_2O \text{ emission} = \sum_{i=1}^{n} (F_i + F_{i+1})/2 \times (t_{i+1} - t_i) \times 24 \quad (2)$$

where: F – GHG flow at the i^{th} measurement; $(t_{i+1} - t_i)$ – time length between two adjacent measurements and n – total measurement number. Finally, total CH_4 and N_2O emission were multiplied by, respectively, 25 and 298 in order to calculate their CO_2 equivalent.

At the end of the experiment, two soil layers from each pot were separated, one from the top to 5 cm depth and the other from the 5 cm to 15 cm depth. The soil from each layer was mixed, and a sample was collected and analysed for pH, dissolved organic C (DOC), ammonium (NH_4^+-N) and nitrate (NO_3^--N) concentration. Soil pH was measured in a 1:5 (v/v) suspension of soil in water. Soil DOC concentration was determined extracting the samples using deionised water with soil to water ratio of 1:10 for 1 h at 100 rpm. Then, the extracts were centrifuged at 20 000 *g* for 10 min and filtered through a 0.45 µm pore-size membrane (cellulose nitrate) to remove particulate C. Finally; the extracts were analysed by a total organic C analyser (DC-80, Rosemount Analytical Inc., Anaheim, USA) after the removal of inorganic C by acidifying the sample. Concentrations of NH_4^+-N and NO_3^--N were determined from 10 g of soil extracted with 100 mL of 2 mol/L KCl (1:10 ratio); then the filtered extract NH_4^+-N and NO_3^--N concentrations were measured by a continuous flow autoanalyser (San System, Skalar Analytical B.V., Breda, The Netherlands).

Calculations and statistical analysis. Significance of the fixed effects of soil type, plant residue species, residue placement and their interactions were analysed using the generalised linear mixed model (GLMM) by the GLIMMIX procedure embedded in SAS software (SAS Institute, Cary, USA). Tukey's *HSD* (honestly significant difference) test at $P < 0.05$ was used for pairwise multiple comparisons of treatments means. Reported data of soil chemical properties are mean values ($n = 3$) expressed on dry weight (DW) basis (105 °C), while, reported GHGs measures are the arithmetic means ($n = 3$) ± standard error. To study the relationship between the investigated soil variables and the soil total GHGs (CO_2, CH_4 and N_2O) emission, Pearson's correlation coefficients

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were calculated by using Proc CORR in SAS v9.2 environment.

RESULTS AND DISCUSSION

Soil CO_2 fluxes during the experiment ranged from a value of 0.01 g/m^2/h to 2.35 g/m^2/h in the Vertisol and from 0.22 g/m^2/h to 5.79 g/m^2/h in the Cambisol (Figure 1). In general, residue addition increased total CO_2 emissions more in the Vertisol (+154%) than from the Cambisol (+42%). Crop residue placement and type increased total soil CO_2 emissions differently in the two soils (soil × residue placement × residue type, $P < 0.0001$). In particular, in the Vertisol, Wh residues increased the total CO_2 emission more than faba bean when left on the

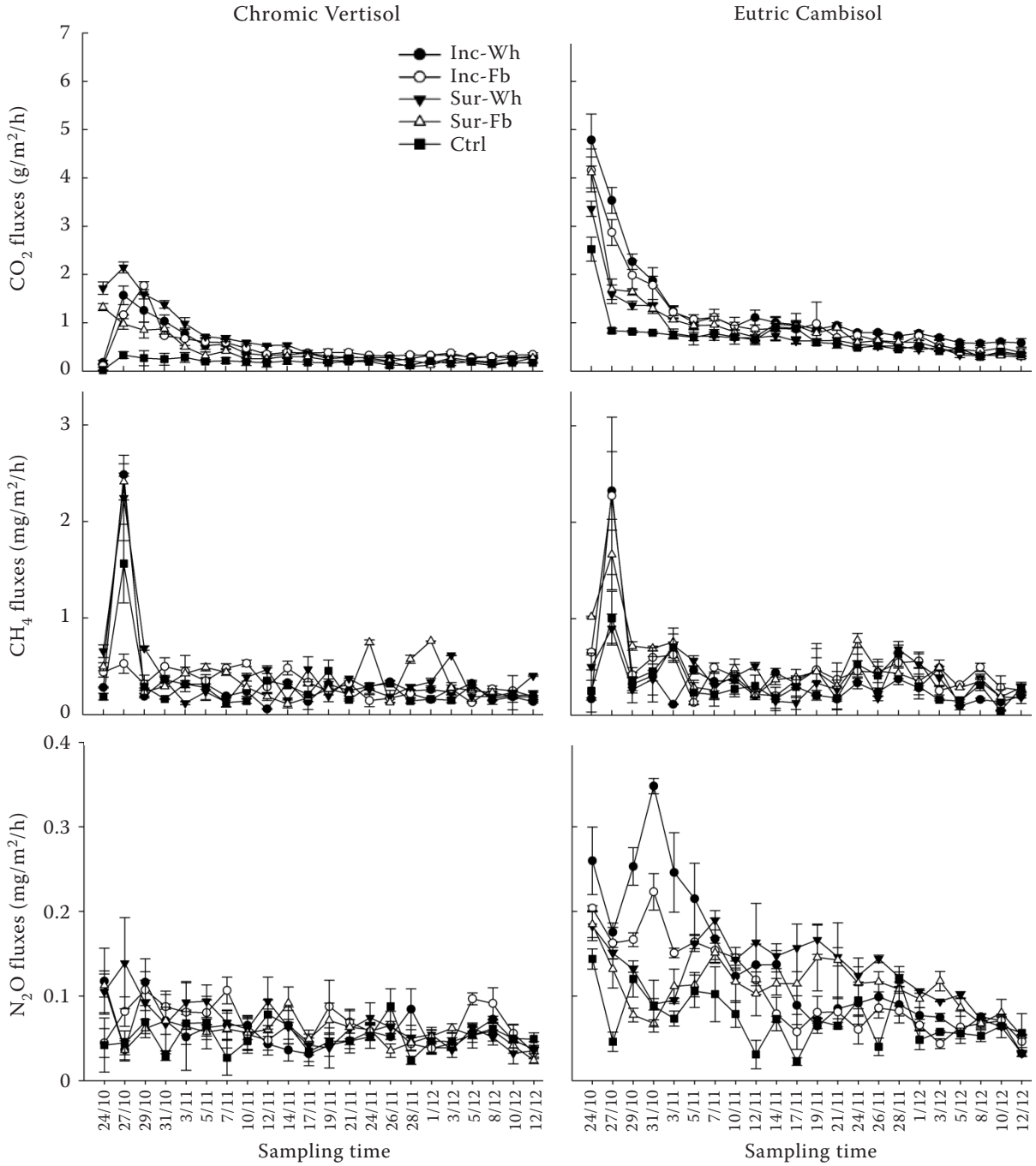

Figure 1. Soil CO_2, CH_4 and N_2O emission fluxes from Chromic Vertisol and Eutric Cambisol amended with faba bean (Fb) and wheat (Wh) residues, incorporated (Inc) or left on the surface (Sur), or unamended (Ctrl) during the experimental period. Data are means ± standard error (n = 3)

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surface (+221%, and +89%, respectively), whereas no differences between residues were found when incorporated (+152% compared to the control, on average) (Figure 2A). In the Cambisol, Fb emitted more than Wh when left in the surface and less than Wh when incorporated (Figure 2A).

Methane emission fluxes ranged from 0.003 to 3.25 mg/m^2/h with values of 0.02–2.73 mg/m^2/h in the Vertisol and 0.003–3.25 mg/m^2/h in the Cambisol (Figure 1). Total CH_4 emission was affected by the interaction among soil, residue type and its placement (soil × residue placement × residues type, $P > 0.05$). In Vertisol, small differences were observed between treatments, and only surface application of faba bean residues showed higher values (+18%, on average). On the contrary, in Cambisol, marked differences were observed only between the residues types with higher emission in faba bean than in wheat treatments (+16%, on average) (Figure 2B).

Nitrous oxide fluxes during the experiment ranged from 0.02 to 0.35 mg/m^2/h, with values of 0.02–0.14 mg/m^2/h in the Vertisol and 0.02–0.35 mg/m^2/h in the Cambisol (Figure 1). There were significant interactions in soil N_2O emission resulting from placement and soil type (soil × residue placement × residues type, $P > 0.01$). In particular, in this soil, the Inc-Fb and Sur-Wh treatments showed higher N_2O emissions (+18%) than Inc-Wh and Sur-Fb. In the Cambisol, Wh addition increased total N_2O emissions by 81% (+20% than Fb) and Fb by the 51% respect to the control, with no differences by the residue placement (Figure 2C).

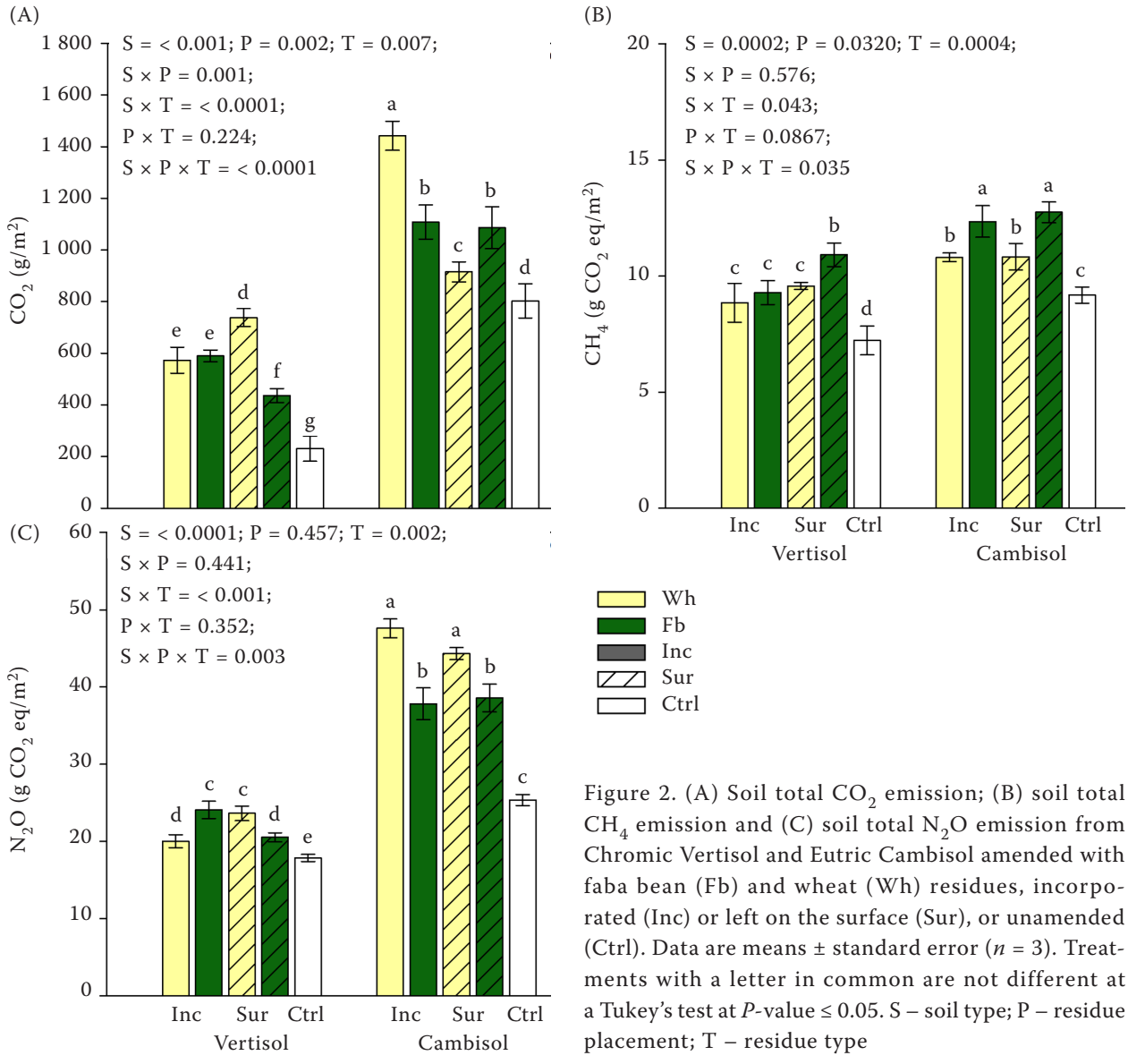

Figure 2. (A) Soil total CO_2 emission; (B) soil total CH_4 emission and (C) soil total N_2O emission from Chromic Vertisol and Eutric Cambisol amended with faba bean (Fb) and wheat (Wh) residues, incorporated (Inc) or left on the surface (Sur), or unamended (Ctrl). Data are means ± standard error ($n = 3$). Treatments with a letter in common are not different at a Tukey's test at P-value ≤ 0.05. S – soil type; P – residue placement; T – residue type

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Table 3. Results of the statistical analysis for the effects of soil type (S), residues management (M), and residue type (T) and their interactions on the variability of soil pH, dissolved organic carbon (DOC), NH_4^+-N and NO_3^--N concentration in 0–5 cm and 5–15 cm soil layers of Chromic Vertisol and Eutric Cambisol soils

	P-values						
	soil (S)	residue placement (P)	residue type (T)	S × P	S × T	P × T	S × P × T
0–5 cm soil layer							
pH	< 0.0001	0.113	0.017	0.002	0.023	0.311	0.034
DOC	< 0.0001	0.070	0.816	< 0.0001	0.300	0.006	< 0.0001
NH_4^+-N	0.002	< 0.0001	< 0.0001	< 0.0001	0.114	0.001	< 0.0001
NO_3^--N	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.125
NH_4^+-N:NO_3^--N	< 0.0001	< 0.0001	0.009	< 0.0001	0.009	0.011	0.011
5–15 cm soil layer							
pH	< 0.0001	0.525	0.329	0.003	0.358	0.012	0.005
DOC	< 0.0001	< 0.0001	0.223	< 0.0001	0.220	0.019	0.025
NH_4^+-N	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
NO_3^--N	< 0.0001	< 0.0001	0.005	< 0.0001	< 0.0001	< 0.0001	< 0.0001
NH_4^+-N:NO_3^--N	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

P-values from PROC GLIMMIX model

The soils studied in this experiment were characterised by contrasting properties resulting in significant differences ($P \leq 0.002$) in their responses (Table 3) in term of pH, DOC and concentration of mineral N forms. And, as described above, with further consequences on GHGs emission.

Crop residue addition had no effect on soil pH of Vertisol regardless of the residue placement. On the contrary, in Cambisol surface application (either for Wh and Fb) and Wh incorporation resulted in a significant strong reduction of pH (–0.5 pH value, on average) in comparison with Fb and control pots (soil × residue placement × residues type, $P < 0.05$) (Tables 3 and 4). This property of the soil control nutrients availability, influence the chemical reactions and can be a useful indicator of soil biochemical processes. In particular, if due to the high soil pH buffering capacity related to its cation exchange capacity, clay texture and carbonate concentration (Luo et al. 2015) no effects were observed in Vertisol, in Cambisol the reduction of soil pH can be related to the soil C and N dynamics and especially to the N mineralisation. Indeed, soil pH reduction was associated with higher NO_3^--N concentration attesting higher mineralisation that could acidify soil by the release of H^+ ions (Chen et al. 2019). This evidence proves that the rapid residue mineralisation was favoured in this kind of soil when residues were left on the surface and when higher degradable wheat was buried. As a consequence, significant correlations between soil pH variations and GHGs emission were found in Cambisol but limited to the incorporation treatment (Table 5). With this regard, Johnson-Beebout et al. (2009) showed that such variation in pH, which is linked to soil redox status, are conducive to the N_2O emissions. In particular, the higher interaction between soil pH (for both soil layers) and residues were significant when the residues were incorporated into the soil showing a negative correlation between pH and CO_2 and N_2O and positive with CH_4 emission (Table 5).

Crop residue placement and type had different effects on DOC concentrations in the 0–5 cm soil layer of the two soils (soil × residue placement and soil × residue placement × residues type, $P < 0.0001$) (Table 3). In the Vertisol, DOC concentrations increased (+27.4%) comparing to the control where residues were incorporated but not when left on surface; in the Cambisol, Fb residues did not show differences between placements whereas Wh had the highest DOC concentration when left on the surface and the lowest when incorporated into the soil. In the deeper layer, both soils showed a similar pattern of DOC concentrations between residues placement showing higher values when incorporated than when left on the surface (+78% in Vertisol and +21% in Cambisol). Within placement, in both soils no differences were observed in surface application among residue types,

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Table 4. Effect of crop residues type and placement (durum wheat or faba bean, and unamended control, incorporated or left in the surface) on pH, dissolved organic carbon (DOC), NH_4^+-N and NO_3^--N concentration in 0–5 cm and 5–15 cm soil layers of Chromic Vertisol and Eutric Cambisol soils

	Chromic Vertisol					Eutric Cambisol				
	incorporated		surface		control	incorporated		surface		control
	wheat	faba bean	wheat	faba bean		wheat	faba bean	wheat	faba bean	
0–5 cm soil layer										
pH	7.8^a	7.7^a	7.8^a	7.9^a	7.8^a	5.4^c	5.8^b	5.3^c	5.4^c	5.9^b
DOC (mg C/kg)	43.2^d	42.5^d	31.8^e	34.6^e	33.6^e	67.6^c	73.5^b	84.4^a	77.2^b	67.2^c
NH_4^+-N (mg N/kg)	3.3^a	1.6^c	0.5^f	0.3^f	1.7^c	1.3^d	0.9^e	2.4^b	1.3^d	0.9^e
NO_3^--N (mg N/kg)	2.4^g	0.4^h	45.1^e	5.7^f	0.3^h	149.6^c	104.6^d	374.8^a	268.1^b	164.5^c
NH_4^+-N:NO_3^--N	1.39^c	4.26^b	0.01^d	0.06^d	6.47^a	0.01^d	0.01^d	0.01^d	0.01^d	0.01^d
5–15 cm soil layer										
pH	7.7^a	7.7^a	7.8^a	7.8^a	7.8^a	5.6^c	5.9^b	5.7^c	5.6^c	5.8^b
DOC (mg C/kg)	83.0^b	75.9^c	45.7^d	43.7^d	48.1^d	93.1^a	86.4^b	70.8^c	77.6^c	91.8^a
NH_4^+-N (mg N/kg)	32.0^a	13.5^b	3.7^d	2.7^d	5.8^c	1.5^e	1.1^f	0.9^f	1.5^e	0.9^f
NO_3^--N (mg N/kg)	0.5^h	0.5^h	3.8^f	1.4^g	0.8^h	43.3^d	36.9^e	76.5^b	90.7^a	66.4^c
NH_4^+-N:NO_3^--N	62.88^a	25.73^b	0.96^d	1.91^d	7.27^c	0.03^e	0.03^e	0.01^e	0.02^e	0.01^e

Within a row, treatments with a letter in common are not different at a Tukey's test at P-value < 0.05

but when incorporated Wh had higher DOC concentrations (+9%, on average) than Fb, regardless of the soil type (soil × residue placement, $P < 0.0001$; soil × residue placement × residues type, $P < 0.05$) (Tables 3 and 4). Crop residue type and placement had strong effects on DOC concentrations of both soil layers in both soil types, with differences associated with the residue placement in terms of C availability. These differences mostly occurred in the Cambisol when wheat residues were added. Such effects have also been reported by Abalos et al. (2013) and were likely a consequence of the high degradability of the wheat compared to the faba bean residues. Indeed, also in our experiment wheat had higher ether extractable C, more hemicellulose and a correspondingly lower fraction of fibre and lignin compared to the faba bean

Table 5. Pearson's correlation coefficients between soil chemical variables and total soil global greenhouse gas (GHG) (CO_2, CH_4 and N_2O) emission in the different soil type and crop residue management

		Chromic Vertisol						Eutric Cambisol					
		incorporated			surface			incorporated			surface		
		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
0–5 cm	DOC	**–0.55**	0.18	–0.26	**–0.68**	**0.48**	**–0.51**	**–0.89**	**0.67**	**–0.71**	**–0.67**	**–0.86**	**0.86**
	pH	–0.16	–0.32	–0.16	–0.15	0.18	–0.19	**–0.92**	**0.96**	**–0.96**	–0.24	–0.09	0.05
	NH_4^+-N	–0.30	–0.18	**–0.82**	**0.62**	**–0.81**	0.25	**0.94**	**–0.86**	**0.88**	**–0.73**	**–0.81**	**0.84**
	NO_3^--N	–0.12	–0.09	**–0.80**	**0.95**	**–0.77**	**0.82**	**0.82**	**–0.94**	**0.96**	**–0.62**	**–0.77**	**0.77**
5–15 cm	DOC	**0.45**	0.09	–0.07	0.31	0.01	**0.59**	**0.81**	**–0.90**	**0.88**	**0.99**	**0.66**	**–0.82**
	pH	–0.18	–0.18	–0.17	–0.06	0.15	–0.34	**–0.87**	**0.93**	**–0.93**	**–0.50**	**–0.86**	**0.77**
	NH_4^+-N	–0.07	–0.19	**–0.76**	**0.93**	**–0.75**	**0.94**	**0.79**	**–0.79**	**0.85**	**0.66**	**0.84**	**–0.85**
	NO_3^--N	0.30	–0.15	0.38	**0.97**	**–0.78**	**0.79**	**0.73**	**–0.77**	**0.83**	**0.65**	**0.79**	**–0.83**
CO_2		–	0.43	0.41	–	**–0.65**	**0.86**	–	**–0.83**	**0.87**	–	**0.69**	**–0.85**
CH_4		**0.43**	–	0.05	**–0.65**	–	–0.56	**–0.83**	–	**–0.97**	**0.69**	–	**–0.93**
N_2O		**0.41**	0.05	–	**0.86**	**–0.56**	–	**0.87**	**–0.97**	–	**–0.85**	**–0.93**	–

Significant values are shown in bold (P-value < 0.05); DOC – dissolved organic carbon

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residues. The different availability of easily accessible labile carbon forms (DOC) was accompanied to significant effects on GHGs emissions (Wilson et al. 2016, Badagliacca et al. 2017). Crop residues increased CO_2 emissions but by different amounts in the two soils, with a clear and positive correlation between DOC availability and/or consumption (lower levels at the end of the experiment) and the total CO_2 emitted in both soils, as also reported by Begum et al. (2014) and Lou et al. (2007) (Table 5). The relatively low respiration rate of the Vertisol is likely to have been a consequence of protection of SOC pools by the higher clay content (Han et al. 2017) and Ca-SOC stabilisation (Shevtsova et al. 2003) coupled with relatively low soil microbial activity due to low C substrate availability, as also demonstrated by Dang et al. (2017) in two contrasting soils. Even so, among the tested soils, a higher increase of CO_2 emission was observed in Vertisol compared to Cambisol, leading to suppose that in this soil a smaller amount of organic matter available was involved in a respiration dynamics led by a soil microbial community characterised mainly by oligotrophic R-strategist microorganisms and low resource efficiency (Ali et al. 2018).

With regard to NH_4^+-N concentration, in the 0–5 cm layer, contrasting responses among soils were observed (soil × residue placement × residues type, $P < 0.0001$) (Table 3). In particular, in the Vertisol residue incorporation resulted in a higher NH_4^+-N concentration than surface application (2.5 *vs.* 0.4 mg N/kg) with higher values in Wh than Fb, whereas no differences between residue types were observed in the surface application, which showed an NH_4^+-N concentration 76% lower than the control. In the Cambisol, the highest NH_4^+-N concentration was observed in Sur-Wh, followed by Inc-Wh and Sur-Fb (–48%, on average), whereas the lowest concentration was observed for Inc-Fb (–62%). In the deeper soil layer (5–15 cm), the Vertisol showed a similar response to the surface layer (Inc-Wh > Inc-Fb > Sur-Wh and Sur-Fb) in term of NH_4^+-N, while in the Cambisol, concentrations in Inc-Wh and Sur-Fb were greater than (+49%) Inc-Fb and Sur-Wh (Table 4).

Soil NO_3^--N concentration in both the 0–5 cm and 5–15 cm soil layers showed an opposite pattern compared to the NH_4^+-N concentration, with surface application of residues increasing nitrate concentration more than residue incorporation and lesser differences by the soil. In particular, soil NO_3^--N concentration in the 0–5 cm soil layer showed a similar response between soils (soil × residue placement × residues type, $P > 0.05$) with higher values in Sur than in Inc and within each placement, Wh was greater than Fb. In the 5–15 cm soil layer, in both soils, higher NO_3^--N concentrations were observed in the surface application (+397% in Vertisol and +108% in Cambisol) than the following incorporation while within each placement major differences between residues types were observed among soils (soil × residue placement × residues type, $P < 0.0001$). In the Vertisol Sur-Wh NO_3^--N concentration was greater than (+173%) Sur-Fb, whereas in the Cambisol a contrasting response between placement treatments was observed with Fb having greater NO_3^--N concentration (+19%) than Wh in Sur while Wh (+17%) was greater than Fb in Inc treatment (Table 4). The release of NH_4^+-N and NO_3^--N from organic residues by mineralisation and nitrification processes can be an indication of the intensity of these processes in the soil. Indeed, in addition to the DOC concentration, low mineral N (NO_3^--N plus NH_4^+-N) concentration, especially NO_3^--N, in the Vertisol compared to the Cambisol, suggest reduced mineralisation from the added organic material (Hijbeek et al. 2018). Soil mineral N concentration is paramount to microbial growth and respiratory processes, and moreover is one of the main factors that determine nitrous oxide emission from soil (Oertel et al. 2016). With this regard, in Vertisol significant correlations were observed between mineral N forms (for both soil layers investigated) and GHGs emission when residues were left into the surface showing positive Pearson's coefficient for CO_2 and N_2O and negative for CH_4. When the residues were incorporated, only the correlations with N_2O were observed (Table 5). In Cambisol, crop residues incorporation highlighted, for both soil layers investigated, positive correlation between N mineral forms and CO_2 and N_2O total emission while negative correlations were observed for CH_4. A different pattern was observed when residues were left on the soil surface with positive correlations for CO_2 and CH_4 while were negative for N_2O (Table 5).

Differences among soil variables directly resulted in opposite trends, in our experiment, in gaseous emissions between residues type and placement. In particular, the placement of crop residues in the Vertisol resulted in very different patterns of C dynamics in the different soil layers. In the surface application, the reduced interaction between residues and soil led to CO_2 emissions being driven by residue type and its degradability. However, when

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residues were incorporated, the role of soil properties was dominant in controlling the response. The concentrations of DOC and NH_4^+-N were higher where residues were incorporated than when they remained at the surface, and it is possible to assume that residue incorporation, particularly in the Vertisol, reduced substrate availability to microbes through fixation of available C and N. In theory, higher substrate availability should have induced a higher respiration rate. However, we found that the absolute difference in the soil respiration of the Vertisol was lower when residues were incorporated than when left on the surface if compared to control. Such a discrepancy may have arisen from the ability of clay to slow down the organic matter decomposition by absorption, interacting with soil microbes and their external enzyme activity or by limiting oxygen diffusion and CO_2 release (Vogel et al. 2015, Datta et al. 2019). And indeed, higher DOC was associated with higher respiration in the sandy Cambisol compared to the clay Vertisol. According to this interpretation, Li et al. (2013) and Datta et al. (2019) found higher emissions for residues placed on the soil surface than for incorporated residues as was the case in our experiment with the Vertisol. This indicates that the incorporation of residues into the soils in our study inhibited CO_2 release, by modifying the availability of resources and oxygen to decomposers and gaseous diffusion from soil pores to the atmosphere.

In the Cambisol, soil CO_2 total emission was linked to DOC concentration in the topsoil and lesser differences of DOC concentration between topsoil and subsoil if comparing to the Vertisol were found. This indicates a more rapid translocation of the DOC from the subsoil to the topsoil, which may have fed the C emissions. For this soil type, our study agrees with Giacomini et al. (2007), who showed more rapid decomposition and higher CO_2 emissions from residue incorporation. In particular, residue incorporation stimulated emission from the more degradable wheat residues. By contrast, in the Cambisol, the differences between DOC concentrations and the total emissions between residue type in soil respiration suggest that CO_2 release from deeper soil layers may have contributed to the total soil CO_2 emission. When residues were applied to the surface, although significant, moderate differences were observed between residue type. This evidence indicates an inhibition of residue decomposition occurring following surface application. The reduction of decomposition and CO_2 emission from residues applied on the soil surface, as argued by Giacomini et al. (2007) and Bremer et al. (1991), can be ascribed to reduced contact between residues and the soil.

What has been observed with regard to residue decomposition, soil respiration and oxygen concentration had consequences on methane fluxes and total emission, as postulated by Ball (2013) and Tang et al. (2015). In particular, in Vertisol it is possible to hypothesise that lower respiration in Sur-Fb, due to the low degradability of this kind of organic matter, leads to higher CH_4 emission as a consequence of the concomitant late residue decomposition in a low oxygen environment, as shown in Figure 1. In the same way, in Cambisol, CH_4 total emission was almost correlated with CO_2 emission, indicating how the reduction of available oxygen in the soil has resulted in the subsequent release of methane (Figure 1). However, it is important to highlight, as shown by the correlation analysis (Table 5), that the total CO_2 and CH_4 emission when crop residues were left on the soil surface in Vertisol or were buried in Cambisol showed a negative correlation between them. This behaviour could be a result of soil methanogenic microorganism's community damage due to an indirect C starvation related to competition for substrates with aerobic microorganisms (Segers 1998).

With regard to N_2O emission, Velthof et al. (2002) observed higher N_2O emissions in sandy soil than in clay soil, in an incubation experiment studying crop residue decomposition, in accordance with the results we observed. As reported by Taylor and Townsend (2010) and Song et al. (2019), soil denitrification is controlled by C and NO_3^--N availability under anoxic conditions or low O_2 availability. As a consequence, in Cambisol, a small variation in the absolute values of DOC and nitrate were likely to have enhanced N_2O emissions, which could have depended on both C and NO_3^--N availability for microbes. Indeed, although no differences were observed between residues management treatments on N_2O emission, these results were a consequence of soil properties driving different processes of residue decomposition, confirmed by the positive correlations shown in Table 5. In particular, following surface application. N_2O total emissions were related to NO_3^--N concentration in the 0–5 cm soil layer, and thus on substrate N availability, in the deeper soil layer lower nitrate concentrations, suggest a stronger link with CO_2 emission and the formation of anoxic microsites inside soil pores where microbes

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denitrify (r = 0.87, Table 5) (Nett et al. 2016). In the same way, the same dynamics could be observed in the Vertisol where the differences between treatments, although significant, were less important. This finding regarding N_2O emissions was also observed by de Ruijter et al. (2010) with leek, broccoli and sugar beet residues and Nett et al. (2016) in an experiment using cauliflower residues. According to these authors, surface application of crop residues doesn't limit microbial activity, because the first cm of soil is characterised by high biological reactivity and by favourable conditions for either aerobic or anaerobic microbial communities.

Total soil GHGs emission, the result of the sum of CO_2, CH_4 and N_2O emitted within the experimental period, for both tested soils and each treatment are presented in Figure 3. In general, CO_2 emission represents about 90–96% of the total GHGs emission, whereas N_2O and CH_4 shown an incidence of about 4.1% and 1.5%, respectively. Although no differences among the two tested soils were observed with regard to CO_2, N_2O emission percentage was slightly higher in Vertisol than in Cambisol. Total soil GHGs emission following the emission of each gas, and especially CO_2, was significantly affected by the interaction between soil characteristics, type of residue and its management (soil × residue placement × residue type, P < 0.0001). In the Vertisol, surface application leads to achieving the highest and lowest total GHGs emission for Wh (+202% compared to the control) and Fb (+83% compared to the control), respectively. Moreover, among these treatments, a higher incidence of CH_4 and N_2O emissions were observed in Fb (2% for CH_4 and 5% for N_2O) than in Wh (1% for CH_4 and 3% for N_2O). An intermediate level of total emission has been observed when residues were incorporated with no difference between residues types (+140% compared to the control) (Figure 3). In the Cambisol, a contrasting trend was observed when Wh residue was applied showing the highest emission when left on the soil surface (+79% compared to the control) and the lowest when buried (+16% compared to the control). Among these treatments, a higher incidence of N_2O emission was observed in incorporation compared to the surface application (5% *vs.* 3%). Fb residue application leads to an intermediate GHGs emission among Wh residues (+27% compared to the control) (Figure 3).

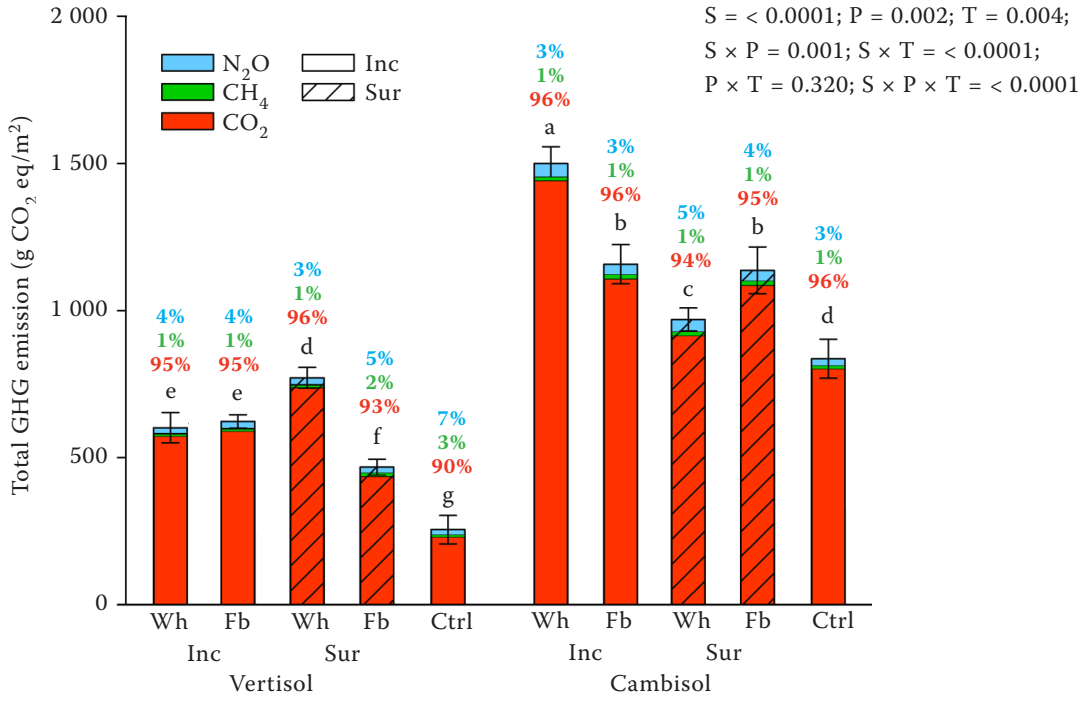

Figure 3. Soil total greenhouse gases (GHGs) emission (CO_2 + CH_4 + N_2O) from Chromic Vertisol and Eutric Cambisol amended with faba bean (Fb) and wheat (Wh) residues, incorporated (Inc) or left on the surface (Sur), or unamended (Ctrl). Data are means ± standard error (n = 3). The percentage value above the bar indicates the relative weight of that gas compared to the total GHGs emission. Treatments with a letter in common are not different at a Tukey's test at P-value ≤ 0.05. S – soil type; P – residue placement; T – residue type

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Our study demonstrated how crop residue decomposition may have different effects on soil properties depending on the management applied, degradability of the residue, and the type of soil that will receive the residue. We also showed that the effects of residue type on soil properties were strong and differed by the soil layer. This occurred despite the residues having similar C:N ratios, which contributed to the observed effects of the residue type on GHGs emission. In particular, our hypotheses were partially confirmed, with higher total emission observed for more degradable wheat residues when incorporated in Cambisol and applied in the surface in Vertisol. These results can be a consequence of the different contact between crop residues and the fine clay particles and the related different gaseous diffusion among soils and in the two management approaches tested. Besides, among GHGs, if CO_2 total emission depended from the interaction between residue type and management, CH_4 and N_2O emission were most influenced by residue type. With this regard, the evidence highlights the effects of the different speed with which the residues make nutrient substrates available for microorganisms and alter the soil environment on the emission of these two gases. The results of this study can have implications for the management of the plant residues when aiming to counterbalance short-term effects on nutrient availability and long-term effects on C accumulation. Finally, our results showed that the clayey Vertisol has a slower decomposition rate, but higher reactivity to management than the sandy Cambisol.

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